THE IONOSPHERIC NANOSATELLITE FORMATION, EXPLORING SPACE WEATHER

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The Ionosphereic Observation Nanosat Formation (ION-F) is a constellation of three satellites being built by Utah State University (USUSat), University of Washington (DawgStar), and Virginia Polytechnic Institute (HokiSat). The program is under NASA Goddard direction but had been started as part of the AFSOR/DARPA University Nanosatellite Program. It has progressed with support from industry, NASA Goddard, the Air Force Research Labs, and the Air Force Space Test Program. The primary scientific objective is to measure the fundamental parameters of ionosphereic density irregularities that effect radio wave propagation including communications, navigation, and the Global Positioning System. This data will also be used in the development and validation of global ionospheric models. Student teams, with direction from faculty and professionals, are designing and building these 15kg three axis stabilized satellites. The satellites will fly as a string of beads, with varying inter-satellite separation, over an approximate one-year mission. Two of the satellites incorporate propulsion systems for controlling the evolution of the string of beads constellation. Navigation will be provided by an onboard GPS system developed by the John Hopkins Applied Physics Lab. ION-F is one of the first tests of a small satellite constellation for making scientific observations of the near Earth space environment.

The Space Weather Effort

Our society relies more and more upon near-Earth space, and the weather within this region affects human activities in many ways. Communication, GPS navigation, satellite ocean altimetry, surveillance, precision geolocation, and over the horizon radar systems all effected by a disturbed ionosphere. Mccoy [1] pointed out that ``the quality of the performance and even their availability depend on the precise specification and forecast of the global ionospheric electron density and knowledge of the presence of ionospheric irregularities and scintillation producing regions''. The ionosphere is the substantial plasma, which surrounds the Earth with global motion driven by the interaction of solar heating, irradiation, the Earth's magnetic field and rotation. The amount of plasma at any on location is controlled by a large number of chemical, radiative, and plasma transport processes in additions to being frictionally moved along with netural atmosphere. The process that drives the creation and convection of the plasma on planetary scales also promotes turbulent structures with a large range of scale sizes.

This complex dynamic system has been studied with in-situ rocket and satellite measurements and ground-based radio, radar, and optical probes. Recently several highly sophisticated empirical and theoretical models have been developed for the study and specification of the global ionospheric climatology and “weather”. At present, one of the major obstacles for better understanding of the ionosphere-thermosphere-mesosphere (ITM) system and the detailed testing and further improvement of global models are the limitations on our understanding of transport processes and of the properties and evolution of atmospheric and plasma structure and waves.

The Science Role for Small Satellites

The scientific community and NASA are continually evaluating and setting the direction of future science missions including those targeted at space weather. These efforts are distributed as road maps or plans such as the Space Science Strategic Plan [2] or the Earth Sciences Enterprise Strategic Plan [3]. Missions, and the required supporting technologies, are outlined in these plans. Many of the future mission concepts require constellations that act as a single mission spacecraft for coordinated observations, in situ measurements, or as a single virtual instrument (for example, interferometry, distributed sensors, or sensor nets). The only conceivable way many of these missions can be achieved is through the use of small satellites. Science objectives benefit either from the populous spacecraft constellations or more frequent flight opportunities due to low cost spacecraft. The Space Science Strategic Plan outlines these needs as “micro or nano-sciencecraft that would have: smaller, more lightweight, more capable and resource-efficient spacecraft “bus” and “payload” components; efficiently integrated bus-payload spacecraft designs;

high performance data compress technology; low power, high performance electronics and micro-electromechanical systems (MEMS) technologies."

An overriding concern of NASA in implementing these constellations of small satellites is cost. These future missions will never occur if the cost of the mission is N times the cost of a current mission, where N is the number of satellites in the constellation. Therefore, the science community is proposing limited and simple instrumentation for the near term missions. The science return occurs from the multi-point or spatial measurements of a simple payload and not from a complex suite of instruments. Some examples of the multi-satellite missions being discussed within the science community for the near term are:

1. A mapping mission of the Earth's magnetosphere using elliptical orbits out to five Earth radii. The primary instrument is a magnetometer.
2. Mapping missions of the Earth's lower ionosphere in altitude using orbits that dip below 200 km and extend beyond 1000 km. The primary instruments are electromagnetic waves and electron density.
3. A mission exploring the time and spatial scales of ionospheric density irregularities. The primary instruments are ionospheric drifts, density and neutral winds.
4. A set of satellites probing the lower atmosphere and troposphere composition through GPS occultation measurements.
5. A large set of satellites providing real time ionospheric data for driving space weather models. Electron density and ion drifts are the primary instruments.

The operational lifetime of these exploratory science missions ranges from 6 months to 4 years and for many the intersatellite separation ranges vary from 10's to 1000's of kilometers within constellations of 3 to 12 satellites. Orbital control is essential to mission success, but control fits into the "loose" category where relative position control to within 20% is acceptable. The science community has proposed even more ambitious projects with constellations of 100's of satellites or constellation control with precision sufficient for interferometery, but these are not low-cost, near-term missions. Most near-term missions require absolute knowledge of spacecraft position in the range of 10 to 100 meters most likely requiring each spacecraft to use GPS for navigation. The formation flying can be accomplished through passing simple GPS positional products between the satellites. The inter-satellite communication needs are modest for the missions outlined characterized by relatively low data rates and low volumes. The type of information to be exchanged is more of an operational "status" message that contains spacecraft orbit, attitude information, and instrument modes of operation. Generally, the spacecraft will use the link to support formation-flying needs of maintaining the relative position of the satellites. The links will be used to distribute control information throughout the constellation, as it may be impossible for every satellite to directly communicate with every other satellite.

These near term science missions envision satellites in the mass in the range of 10 to 50 kg with instrument power requirements in the range of order of 3 to 15 watts. Attitude control is expected to within 5 degrees but attitude determination is typically required at the 0.1-degree or better level to unfold the scientific results from the observations. The realization of these missions is thought to require the miniaturizing of components and the integration of similar functions across subsystems to reduce fabrication cost and size. For example, all sub-system electronics, including communications, might be integrated within the command and data processing subsystem (C&DH). This approach introduces offers significant power and mass savings over traditional approaches. Technology investments are required to adapt commercial electrical components to the expected radiation environment especially for modern, low-power components. Spacecraft autonomy will be needed to reduce operations costs with ripple effects for every subsystem. To make these constellations practical the ground systems must be kept inexpensive, simple, with inter-satellite communications to implement autonomy across the constellation. The Ion-F program to be discussed next has provided a test bed for these several ideas and a test bed for the constellation class small science satellite.

The Ionosphereic Observation Nanosat Formation History and Status

The Air Force Office of Scientific Research (AFOSR) and the Defense Advanced Research Projects Agency (DARPA) jointly solicited and funded a number of universities to each design, build, and fly a nanosatellite. The universities, under this program, were to make use of student labor and pursue low-cost space experiments that explore useful applications or technologies of interest to the Air Force. The Air Force Research Labs (AFRL) was given the management responsibilities for the University Nanosatellite Program and the launch was to be provided by the Air Force Space Test Program. The universities in the University Nanaosatellite program were encourage and expected to obtain additional funding from other source including other government agencies, cost sharing, and industry donations.

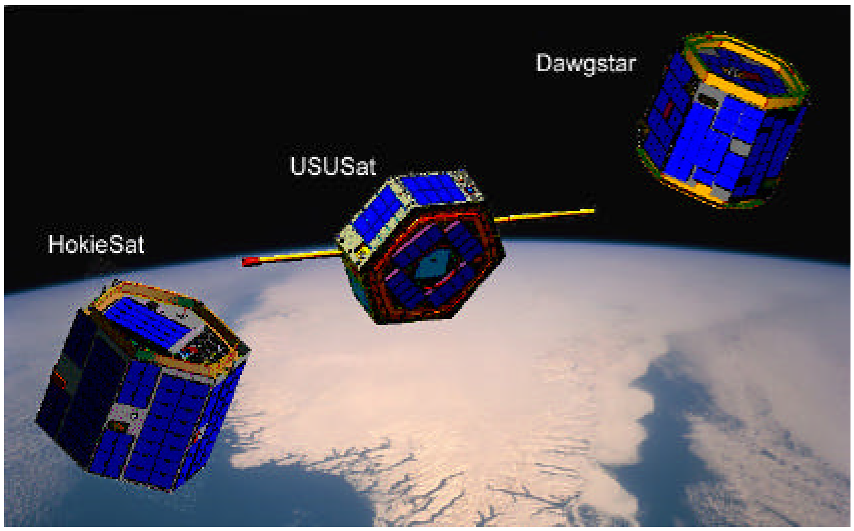

Figure 1 The three satellites of the ION-F mission

In January of 1999 AFRL committed the program to a launch on the Space Shuttle through the Space Test Program (STP) and helped organize Utah State University, along with the University of Washington and Virginia Polytechnic Institute into a team, called ION-F, for a joint shuttle launch. Each of these universities is developing a 15-kg spacecraft as part of the ION-F constellation. They have been given the names "USUSat" – Utah State University, "Hokiesat"- Virginia Polytechnic Institute, and "Dawgstar" – University of Washington by the various student teams as illustrated in Figure 1. The objectives of the Ion-F satellites are to

- Investigate global ionospheric structures that degrade the performance of space-based radars, communications, and other distributed satellite networks.
- Test autonomous formation flying and intersatellite communication technologies.
- Fly new small satellite technologies including micro-thrusters, magnetic gimbaled attitude control, and an internet based operations center.
- Bring a unique, hand-on space experience to students in space systems engineering

In June of 1999 the NASA Goddard Space Flight Center funded the ION-F team through its Cross Enterprises Program to fly a combination GPS navigation and inter-satellite communications cross link system being developed by the Applied Physics Lab. The program also included funding to work and collaborate with NASA Goddard on formation flying algorithms.

In January of 2000 the office of space science funded a proposal submitted to the MITM Suborbital Program lead by Utah State University named "ION-F" Science. The objective is to study the spatial scales, evolution, and global distribution of ionospheric plasma structures. The technical approach was to fly the same low impact instrumentation on each of the ION-F satellites and make the first multi-satellite measurements of these ionospheric structures. The multi-point measurements allow one to resolve the time and spatial coordinates in a drifting ionosphere and the ability to probe the evolution of ionospheric structures on time scales much shorter than an orbital period of a satellite. The award funded Utah State University to provide plasma impedance probes for each of the ION-F satellites and the engineering required for accommodating the probes. The experiment was presented to NASA as very high risk since the construction of the satellites would involve student design and labor and the total funding for the ION-F program is low.

In August of 2001 AFRL recognized that the decision to fly ION-F on the Space Shuttle had placed a significant burden upon the universities. The program was required to conform to documentation and manufacturing standards for the Space Shuttle. This level of detail was unexpected under the original program but has been required by NASA Space Shuttle Safety. Safety related issues have contributed more than one and a half year's delay to the ION-F program. The delays forced substantial costs at AFRL for the and by December of 2001 the costs of delays were beyond what AFRL was willing to cover. AFRL entered into discussions with the ION-F Universities and Goddard in January of 2002 over how to deal with the program delays. AFRL decided to withdraw support for flight of the ION-F spacecraft through the Air Force Space Test Program and to withdraw programmatic overview. Goddard decided to take over programmatic overview and support the shuttle flight which is now expected in late 2003 in 2003.

The Utah State University and the ION-F student teams have made substantial progress towards delivering the nanosatellites for mechanical integration and testing. They have completed critical design reviews and have passed the NASA Phase 0/1 Safety review at Johnson Space Center. The teams have completed and tested engineering models of key components. Flight hardware is being fabricated and assembled at each of the ION-F schools. Development still continues on a few subsystems. A quick overview of each of the spacecraft is presented in the following table organized by subsystem and satellite.

	USU (USUSat)	**Virginina Tech (Hokiesat)**	**UW (Dawgstar)**	**Notes**
Structure	Flight in fabrication	Flight completed	Flight completed	
Power Sub System	Engineering unit tested, flight unit in fabrication	Engineering unit in testing.	Engineering unit tested, flight unit in testing	
Thermal	Analysis and design complete, in testing	Analysis proceeding	Analysis proceeding	USUSAT model applied to all
RF/Communications and Data Handling	Uplink - engineering unit tested, flight hardware in fabrication Downlink – engineering unit tested, minor redesign proceeding Some flight hardware fabricated about 80% complete			All satellite identical USU developing hardware.
Command and Control	Flight hardware in fabrication, Engineering units in testing at VT and UW. Operating system and development environment complete			All satellite identical USU developing hardware.
Software	High level code 50% complete Low level code 80% complete Testing continuing with engineering hardware			UW, VT developing formation flying code
Attitude Control	Flight hardware in fabrication	Flight hardware in fabrication	Flight hardware complete	USU, VT magnetic UW - thruster
Propulsion	None	Flight hardware being qualified	Flight hardware being qualified	
Science Instrument (plasma probe)	Flight Hardware in Fabrication	same	same	USU building for all universities
APL GPS/Crosslink	Flight hardware tested, awaiting long lead S-band preamplifiers			All Universities
Integration and test	Beginning for all spacecraft as flight hardware becomes ready			About 10% complete for entire program

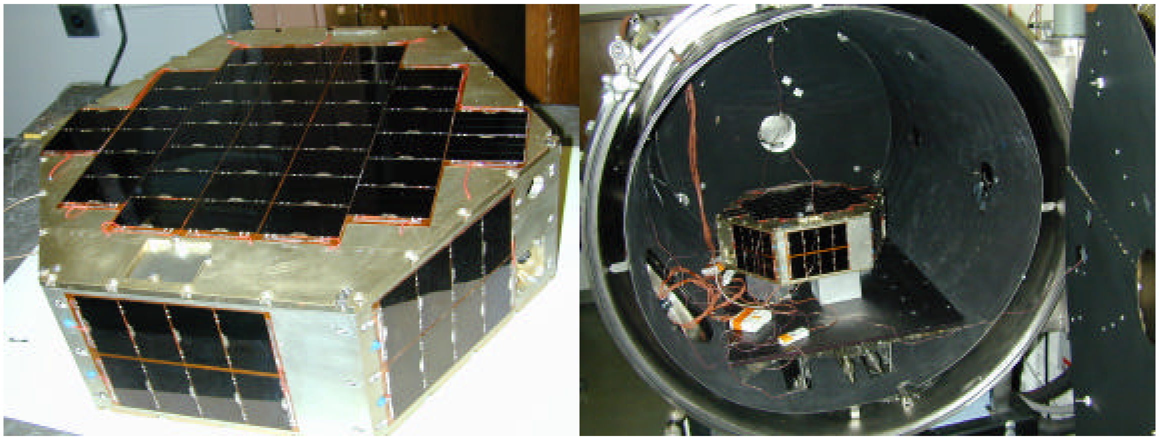

Figure 2 USUSat engineering spacecraft in thermal vacuum testing at the Utah State University Space Dynamics Laboratory

The USUSAT engineering model was delivered to the Air Force for thermal vacuum testing in March of 2002. Prior to delivery it was thermal vacuum tested at the Space Dynamics Lab as show in Figure 2. The components tested included the entire power system, solar cells and batteries, the command and control systems, attitude determination system, and thermal control system. The subsystems not tested were the telemetry components such as encoder electronics, receiver and science instruments. All components were tested over the range of -35C to 70C under vacuum and successfully operated both on internal and external power and with a solar simulator. Software running on USUSAT simulated operations and communicated with the ground station computers external to the chamber.

A Systems Overview of ION-F and USUSat

The ION-F Satellites have been discussed in several reports and thesis published by the principal investigators and students working on the project [4-39]. The ION-F satellites are novel and fairly ambitious projects for universities. The Space Dynamics Lab at Utah State University has provided the infrastructure and technical support for the development of USUSat. The other ION-F spacecraft share considerable commonality with USUSat. We present a brief systems overview of ION-F in general but USUSat specifically.

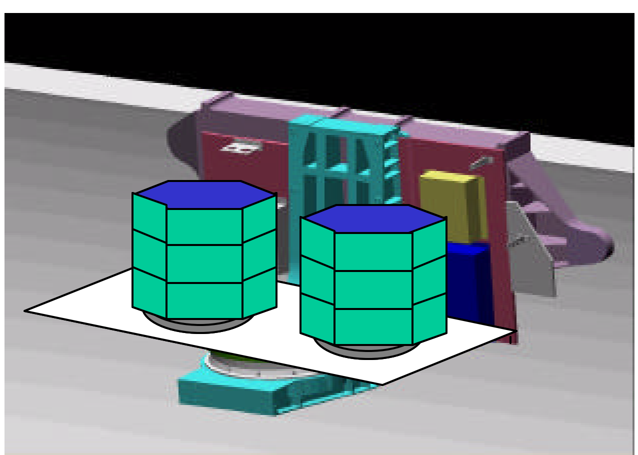

Figure 3 The deployment system for the Ion-F satellites consisting of the SHELS and the Air Force Multi Satellite

The Ion-F constellation is designed to be launched on the space-shuttle on an International Space Station Servicing Mission. The spacecraft will be deployed from the ISS as a stack using a Shuttle Hitchhiker Experiment Launch System (SHELS), which is a ``can less'' ejection system for payloads up to 400 lbs. This launch constrains the mission to a 51.5° inclination orbit slightly lower that the space stations altitude range of 390 to 410 km and at local time of the space stations orbit. The deployment system is shown in `Figure 3` with two sets of three small satellites located on the Air Force Multi Satellite Deployment System and pictured as if inside the Space Shuttle cargo bay. It is uncertain at this time if the ION-F satellites will be launched alone or with a second set of satellites. The lifetime of the ION-F constellation is difficult to predict due to its strong dependence on solar activity, characterized by the 10.7 cm solar flux index. The other major factor affecting the orbit decay is the ballistic coefficient, cross sectional area to mass ratio, of the satellite. USUSat will fly in a low drag orientation for the majority of the mission giving an 8 to 12 month mission. The other two Ion-F satellites will have some propulsive capabilities via a pulse plasma thruster experiment that will extend its lifetime beyond the drag limited life. An ION-F satellite will sweep through all local times in about 30 days.

The three satellites of the ION-F constellation, given a low relative separation velocity, are constrained by orbital mechanics to remain in essentially the same orbital plane. The satellites, either controlled or uncontrolled, will spread out like a string of beads along a nearly common orbit. The objective of the formation flying technology demonstration is to control the intersatellite distance. To do this each satellite will adjust is altitude relative to the other satellites using either variable drag (USUSat) or pulse plasma thrusters. The along track velocity will then increase or decrease thus effecting a change of separation over time.

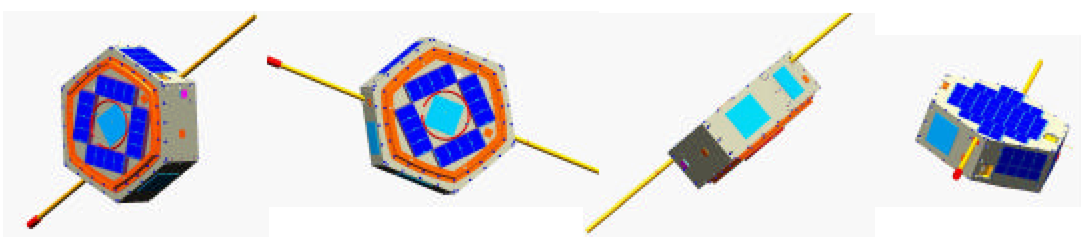

Figure 4 USUSat with booms deployed

The structure for each satellite is hexagonal with an approximate 18 in. (457 mm.) width and a 10 in (127 mm) height. The structures consist of aluminum isogrid and each satellite weights about 16 kg. Three ``light band'' systems developed by Planetary Systems Corp. (PSC) be used to connect and separate the three ION-F satellites and the base plate of the SHELLS platform. Two approximately 0.5 meter booms will be deployed from the USUSat structure for the plasma impedance probe as shown in `Figure 4`. One of the booms will also be used to deploy a magnetometer away from the spacecraft body. The other two ION-F spacecraft will make use of novel patch antennas for sensing the ionospheric plasma and body mounted magnetometers.

A functional block diagram of an ION-F satellite is presented in `Figure 5` (left). The power subsystems are different for each of the satellites. They are all solar cell/battery designs, but USUSAT is using a direct energy series shunt design, UW is using a series boost regulator, and VT is using a direct energy parallel shunt design. All systems make use of advanced triple junction solar cells form TecStar but in different series combinations and buss voltages. The battery designs make use of high-grade commercial industry battery technology NiMH for USUSat and NiCd for the others.

A highly integrated suite of electronics has been developed for ION-F that implement command and control, attitude determination, and telemetry. The entire electronics are shown in `Figure 5` (right) as a red box located in the top half of USUSat. This C&DH system is based upon industrial-grade components including the Hitachi SuperH RISC Processor and radiation tolerant ACTEL gate arrays. The memory subsystem contains 256 Kbytes of PROM, 8 Mbytes of redundant flash memory, and 7 Mbytes of SRAM.

The C&DH system als o contains a 16 Mbyte telemetry buffer, digital and analog interfaces, and a DMA-oriented CMOS camera frame buffer. The cameras are used as horizon sensors for attitude determination.

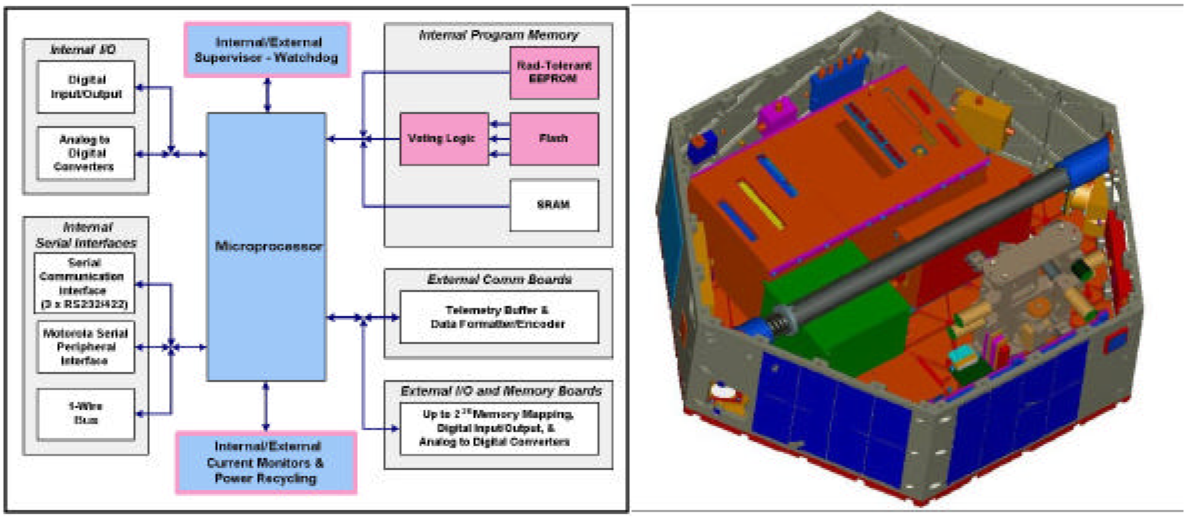

Figure 5 A systems level diagram of an ION-F Satellite and an internal view of USUSAT.

The system is only hard to approximately 5k Rad total dose. Single event upsets are dealt with at the hardware level by current monitoring circuitry, redundant voting memory configurations and watchdog timers. The entire computer system consumes less than 1.25 watts and provides an 80-MIPS, 32-bit computation platform for small spacecraft. This C&DH system makes use of the commercial technology developed for the PDA market and is similar to the HP Jornada®, but with additional input and control capability in a radiation tolerant design. The system has been fabricated and is composed of boards for CPU, IO, Telemetry, Camera interface. The VxWorks real time operating system and development environment is employed and the common electronics have been successfully operating for approximately 1 month in a space simulation thermal vacuum chamber for the Air Force

The Ion-F Satellites will have full uplink and down link capability and a high speed data dump capability to two dedicated ground stations at Utah State University and Virginia Tech. The system is built around a combination of commercial aerospace parts, amateur equipment, and custom built hardware. The system is all digital using simple frequency shift keying for modulation. A 9600 bit/s uplink at 450 MHz is shared among the ION-F spacecraft using AX.25 packet radio protocol. Each satellite has a 115.2 kbit downlink at S-band with a PCM format. The S-band downlink is allocated such that 9600 bit/s is dedicated to command downlink and the remainder is used to download the solid state telemetry recorder of science and instrument status data. Each of the three satellites will use the same telemetry formats and share the same ground stations.

Conclusion

The students working on the ION-F Satellites have the hardware about 75% complete. Software development is well underway with the major milestones of having the real time operating system running and low-level driver software 90% complete. Testing of the RF communications link, system level testing and high-level software development and most importantly safety documentation are the remaining major tasks. The common electronics that have been developed for the ION-F satellites are astounding in that they consume less than 2 watts and include mass storage, attitude determination (cameras), and attitude control functions. They provide the power of a 90 MHz Pentium processor and are flexible enough for other small satellites.

The USUSat program will be undergoing a major change over of students over the summer of 2002. This will be a challenging period as funding is now short and a new set of students need to be trained on the project. The ION-F project will require quality leadership and technical help industry and NASA to reach competition. Additional funding will be required for fiscal year 2003 and also for mission operations. It is unlikely that the launch of ION-F could occur before the late fall of 2003 given that it takes approximately 6 months after delivery of the spacecraft to get through space shuttle test and integration procedures and detailed testing has been proposed by Goddard.

The ultimate question is will ION-F be successful and completed. All parties are still dedicated to completing the project but the definition of success can "spun" in different ways. Ultimate success will be to have three operational spacecraft making ground breaking measurements as a constellation of the Ionosphere as shown in Figure 6, but the ION-F program is still a very high risk program. ION-F has already been very successful in demonstrating how multiple subsystems can be tightly integrated into a common electrons package for small spacecraft this is very low power, low mass, and still be yet capable. To a large extent the systems engineering has been driven by the needs of the space science community for space weather type studies. In this sense ION-F has been somewhat successful already.

The greatest success of the ION-F program has been with the students who have worked on the program. Over 30 undergraduate students have contributed and completed senior design projects, 20 MS students, and 3 PhD students have worked just on USUSat. The mentoring and training of the next generation of engineers, scientists, and program managers working within the space industry is of vital interest to both governments and private industry. The demand for qualified individuals who have experience in designing, developing, and managing satellite projects has only been increasing over the last decade. An experienced workforce by definition is one that has completed programs, learned from mistakes, and is ready to apply lessons learned. Creating a new experienced workforce is both a time and financial concern. Time, since it may take years for conventional space programs to run through the program cycle of conception, design, testing, and flight. Financial, since the delay or failure of a space system due an inexperienced workforce is unacceptable. The need is keen for qualified space systems engineers and program managers across all types of organizations.

The university system, at least within the United States, has not been actively engaged in providing training for a new generation of space systems engineers. We believe this is correlated with the relative lack of satellite systems research going on within the universities. We also believe the government and satellite industry can only benefit from the infusion of university research and new ideas. The University Nanosat Progam was started by the Air Force to encourage spacecraft systems research within the United States universities and to speed the development of an experienced workforce at lower cost. To this extent ION-F has been very successful.

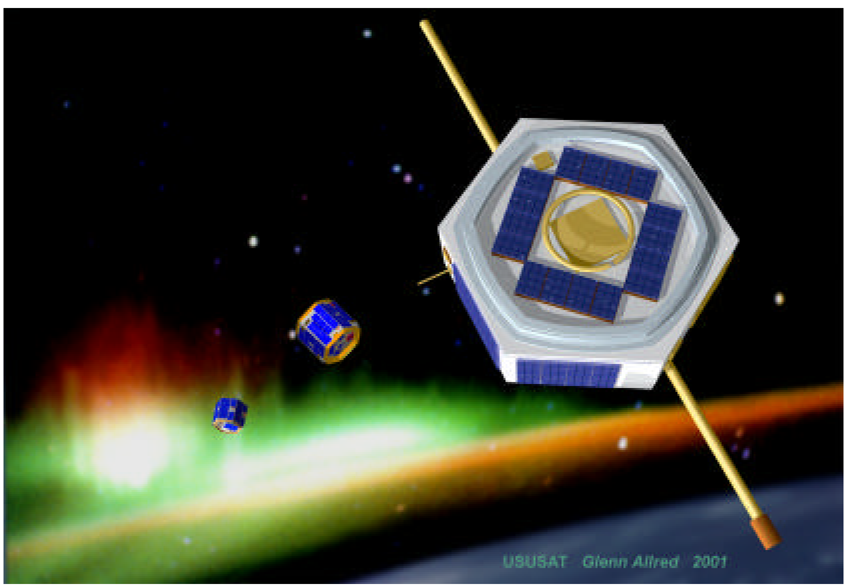

Figure 6 An artistic impression of the ION-F Constellation in flight.

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